PB83-240820

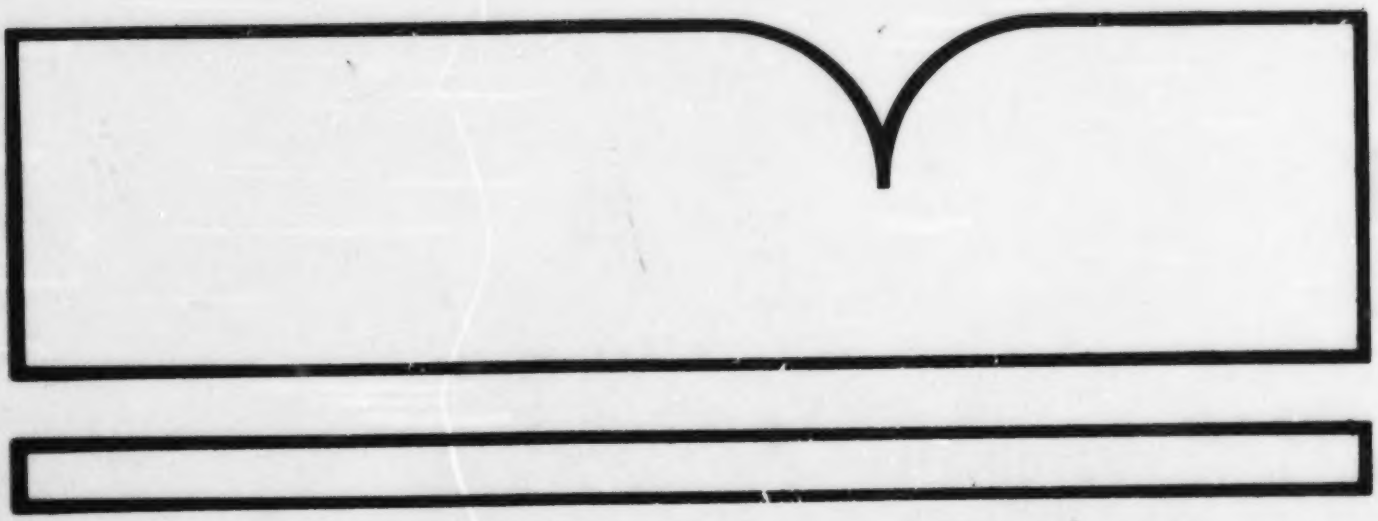
Microorganisms and Higher Plants for Waste Water Treatment

(U.S.) National Space Technology Labs.
NSTL Station, MS

Prepared for

Robert S. Kerr Environmental Research Lab.
Ada, OK

1983



U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before comple

1. REPORT NO.	2.	3 PB83-240820
EPA-600/J-83-032		

4. TITLE AND SUBTITLE	5. REPORT DATE
MICROORGANISMS AND HIGHER PLANTS FOR WASTE WATER TREATMENT (Journal Version)	1983
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
B.C. Wolverton, R.C. McDonald, and W.R. Duffer	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
National Aeronautics and Space Administration National Space Technology Laboratories NSTL Station, Mississippi 39529	CAZB1B
	11. CONTRACT/GRANT NO.
	IAG AD80F2A104
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Robert S. Kerr Environmental Research Laboratory U.S. Environmental Protection Agency P.O. Box 1198 Ada, OK 74820	Journal Article
	14. SPONSORING AGENCY CODE
	EPA-600/015

15. SUPPLEMENTARY NOTES

REF: J. of Environmental Quality 12(2):236-242 (1983)

16. ABSTRACT

Batch experiments were conducted to compare the waste water treatment efficiencies of plant-free microbial filters with filters supporting the growth of reeds (Phragmites communis), cattail (Typha latifolia), rush (Juncus effusus), and bamboo (Bambusa multiplex). The experimental systems consisted of two components in series. The first component was an anaerobic settling-digestion container. The second was a "non-aerated" trough filled with rocks, decreasing from large rocks (up to 7.5-cm diam) at the bottom , to pea gravel (0.25- to 1.3-cm diam) at the top. The plant-free microbial filter was equally effective in carbonaceous BOD_5 (5-d biochemical O_2 demand) removal. The vascular aquatic plant series enhanced ammonia removal, and consequently improved nitrogenous BOD_5 removal. Under the conditions of these experiments, raw sewage with initial BOD_5's of 100 mg/l can be upgraded to meet secondary standards with 6 h in component 1, and 6 h in a plant-free filter or filter using cattail, rush, or reed. When initial BOD_5's are approximately 450 mg/l, 24 h in component 1, 29 h in a reed filter are required to meet secondary standards. Total N removal studies were conducted, which demonstrated that a reed system is capable of removing NO_3-N and NH_3-N simultaneously, probably through a common NO_2-N intermediary, then to N_2. Overall, the reed system was superior to all others evaluated in this research project.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Effluents--sewage treatment	Vascular aquacit plants	06B
Water pollution	Nutrient removal	06F
Aquaculture	Emergent Vegetation	98F
Reed--microbial filters		68D

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	8
	20. SECURITY CLASS *(This page)*	22. PRICE
	UNCLASSIFIED	

EPA Form 2220-1 (9-73)

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA-600/J-83-032
JOURNAL ARTICLE

Reprinted from the *Journal of Environmental Quality*
Vol. 12, no. 2, April–June 1983, Copyright © 1983, ASA, CSSA, SSSA
677 South Segoe Road, Madison, WI 53711 USA

Microorganisms and Higher Plants for Waste Water Treatment[1]

B. C. WOLVERTON, R. C. MC DONALD, AND W. R. DUFFER[2]

ABSTRACT

Batch experiments were conducted to compare the waste water treatment efficiencies of plant-free microbial filters with filters supporting the growth of reeds (*Phragmites communis*), cattail (*Typha latifolia*), rush (*Juncus effusus*), and bamboo (*Bambusa multiplex*). The experimental systems consisted of two components in series. The first component was an anaerobic settling–digestion container. The second was a "nonaerated" trough filled with rocks, decreasing from large rocks (up to 7.5-cm diam) at the bottom, to pea gravel (0.25- to 1.3-cm diam) at the top. The plant-free microbial filter was equally effective in carbonaceous BOD, (5-d biochemical O_2 demand) removal. The vascular aquatic plant series enhanced ammonia removal, and consequently improved nitrogenous BOD, removal. Under the conditions of these experiments, raw sewage with initial BOD,'s of 100 mg/L can be upgraded to meet secondary standards with 6 h in component 1, and 6 h in a plant-free filter or filter using cattail, rush, or reed. When initial BOD,'s are approximately 450 mg/L, 24 h in component 1, 29 h in a reed filter are required to meet secondary standards. Total N removal studies were conducted, which demonstrated that a reed system is capable of removing NO_3-N and NH_3-N simultaneously, probably through a common NO_2-N intermediary, then to N_2. Overall, the reed system was superior to all others evaluated in this research project.

Additional Index Words: **microbial filter, *Phragmites communis*, *Typha latifolia*, *Juncus effusus*, *Bambusa multiplex*, domestic waste water.**

Wolverton, B. C., R. C. McDonald, and W. R. Duffer. 1983. Microorganisms and higher plants for waste water treatment. J. Environ. Qual. 12:236–242.

Domestic waste water treatment is one of the major problems confronting every community and city in the United States. Presently, aerobic treatment processes are used almost exclusively in large and small cities in the United States. The activated sludge process is used for large cities; the trickling filter process and facultative lagoons are more popular for small cities.

The least expensive systems are lagoons, which depend on algae to supply O_2 photosynthetically. The other two major aerobic processes require much larger initial investments to design and construct, and have higher operational costs (personnel and energy). The projected costs associated with these systems, mainly due to the inflation of energy prices, have caused a surge in the development of alternative biological processes such as the one contained herein.

Anaerobic processes have low energy requirements, compared with aerobic processes, which need either mechanical aeration or liquid distribution systems. The anaerobic cycle depends on microorganisms that live in the absence of free O_2 and utilize chemically bound O_2. This process received little attention in waste water treatment during past years because of slow bacterial growth rates and sensitivity of the microorganisms to variables such as temperature, pH, shock loading, etc. Recent advancements have helped revive interest in anaerobic filter technology (Jewell et al., 1981; Koon et al., 1979; Switzenbaum and Jewell, 1978; Young and McCarty, 1969). The anaerobic filter method is an attached-growth process in which rock or an inert media is used to provide a stable surface area for microbial attachment and growth. Therefore, microorganisms are partially retained in the system as the waste water passes through. Mean cell residence times of approximately 100 d can be achieved with short hydraulic retention times (Metcalf & Eddy, Inc., 1979).

Interest in the anaerobic filter comes at a time of active research in the use of vascular aquatic plants for waste water treatment (Dinges, 1978; Duffer and

[1] Research results obtained through a joint agreement between the National Aeronautics & Space Administration, and the U.S. Environmental Protection Agency under the EPA/NASA Sub-Agreement EPA 80-D-X0740 at the National Space Technology Laboratories (NSTL), NSTL Station, MS 39529. Received 29 Mar. 1982.

[2] Senior Res. Scientist, NASA/NSTL; Res. Chemist, NASA/NSTL; and Res. Aquatic Biologist, USEPA/Robert S. Kerr Environ. Res. Lab., respectively.

Moyer, 1978; O'Brien, 1981; Stephenson et al., 1980; Tourbier and Pierson, 1976; Wolverton, 1979; Wolverton and McDonald, 1979). A hybrid system that consisted of a microbial attached-growth filter in which reeds (*Phragmites communis*) were rooted was studied by Wolverton (1982) and found to be a very effective system, superior to an anaerobic filter without the incorporation of higher plants. In this study, as well as those contained in this report, sealed chambers were used as anaerobic settling tanks to hold the freshly collected waste water for 24 h prior to transferring it to the filter. The settling tank is especially necessary for the design of a system serving a community, in order to prevent filter clogging.

This paper contains basic waste water data obtained during screening studies to evaluate and compare the effectiveness of cattail (*Typha latifolia*), rush (*Juncus effusus*), and bamboo (*Bambusa multiplex*) with that of reed in similar microbial filter–vascular plant waste water treatment systems. New reed experiments were conducted using waste water with high 5-d biochemical O_2 demand (BOD_5) (> 300 mg/L BOD_5), produced by mixing 1 part water hyacinth juice with 19 parts raw sewage in order to ascertain its maximum capacity. Water hyacinth juice was used to elevate the BOD_5, because it provides a natural concentrate of carbohydrates, proteins, and minerals.

Recognizing at the end of these series of batch experiments that a significant conversion of ammonia-N (NH_3-N) to a nonorganic form occurred as indicated by a corresponding decrease in Kjeldahl N, further experiments with nitrate-spiked solutions were also performed to examine the total N picture.

MATERIALS AND METHODS

Experimental System Design

Six separate experimental systems such as the one shown in Fig. 1 were maintained in a greenhouse. Each system consisted of two components in series. The first component was a plastic, covered reservoir with 113-L capacity, which was used as the anaerobic settling tank. The second component was a galvanized steel trough filled to a depth of 16 cm with railroad rocks (2.5–7.5 cm in diam) and to a depth of 5 cm with pea gravel (0.25–1.3 cm in diam). The trough containing reed, and a second trough free of plants, measured 50.5 cm wide by 30.5 cm deep by 298 cm long. The other 4 troughs were 50.5 cm wide by 30.5 cm deep by 183 cm long. Of these troughs, one each was planted with cattail, rush, and bamboo. The fourth trough was kept free of higher plants. Each trough was fitted with a bottom valve on the end opposite where the anaerobically settled waste water was added, to collect samples and drain the tanks.

Experimental Procedures

In January and February 1981, two anaerobic systems were used to perform the following study. The trough in the first system was plant-free; the second trough contained reed. For each system, 82.6 L of raw sewage was mixed with 4.4 L of fresh water hyacinth juice in order to significantly elevate the BOD_5. The water hyacinth juice was obtained by processing fresh water hyacinth through a portable, electric screw press built from a design provided by Dr. Larry Bagnall, University of Florida. Aliquots were removed from the settling tank initially and after 24 h. The settled and partially digested waste water was pumped into the troughs, and aliquots were removed at 6-, 24-, and 48-h inter-

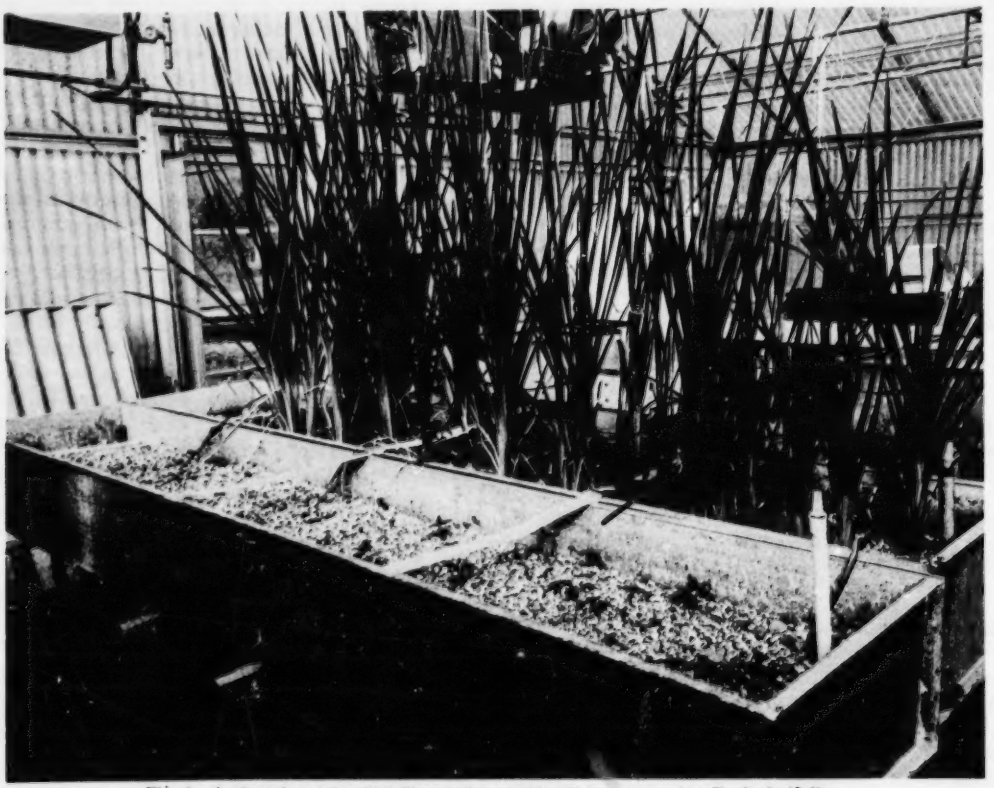


Fig. 1—A plant-free microbial filter and a combination system using *Typha latifolia*.

Table 1—Mean, standard deviation (σ), and upper limit (U) concentrations ($P = 0.95$) of the BOD_5, TSS, and TDS after settling for 24 h, followed by microbial filter treatment with and without plants.

Parameter	Microbial filter	Concentration														
		Settling tank						Microbial filter								
		Initial		6 h		24 h		6 h			24 h			48 h		
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	U	Mean	σ	U	Mean	σ	U
		mg/L														
BOD_5†	Plant-free	114.5	27.3	66.2	25.0	61.6	23.9	17.4	11.2	37.3	8.2	4.8	16.7	6.2	4.4	14.0
	Bamboo	114.5	27.3	66.2	25.0	65.8	23.0	31.4	18.6	64.6	21.4	13.0	44.5	13.0	12.5	35.2
	Rush	114.5	27.3	66.2	25.0	67.2	23.1	17.8	12.2	39.4	7.4	5.5	17.2	3.1	2.2	7.1
	Reed	109.9	34.2			71.7	22.8	8.9	6.3	20.5	2.8	2.4	7.1			
	Cattail	116.8	27.2	94.2	32.4	80.1	32.6	17.4	14.7	44.8	10.4	8.3	25.7	5.2	3.4	11.6
TSS§	Plant-free	54.4	18.7	30.9	12.2	25.0	6.9	12.7	4.0	19.8	10.9	7.5	24.3	3.9	9.7	
	Bamboo	54.4	18.7	30.9	12.2	23.0	8.8	17.1	12.2	38.9	7.0	4.9	15.7	8.4	10.6	27.3
	Rush	54.4	18.7	30.9	12.2	24.8	10.7	17.5	7.2	30.3	13.9	5.8	24.3	4.4	5.9	14.9
	Reed	68.4	34.6			36.0	20.4				5.9	4.6	14.4			
	Cattail	64.4	37.6	34.4	11.9	29.0	8.1	11.6	7.0	24.7	15.3	17.9	48.6	8.6	9.8	28.8
TDS¶	Plant-free	376	79	360	96	361	73	374	73	503	391	83	539	405	88	561
	Rush	376	79	360	96	376	83	452	106	641	467	133	704	466	149	731
	Reed	376	79	360	96	387	96	455	60	563	487	72	616	528	101	709
	Cattail	371	48	327	62	337	28	398	32	468	416	66	539	419	71	551

† BOD_5 = 5-d biochemical O_2 demand.
‡ Data published by Wolverton, 1982.
§ TSS = Total suspended solids.
¶ TDS = Total dissolved solids.

Table 2—Mean, standard deviation (σ), and upper limit (U) concentrations ($P = 0.95$) of the TKN, NH_3-N, and TP after settling for 24 h, followed by microbial filter treatments with and without plants.

Parameter	Microbial filter	Concentration											
		Settling tank				Microbial filter							
		Initial		24 h		6 h			24 h			48 h		
		Mean	σ	Mean	σ	Mean	σ	U	Mean	σ	U	Mean	σ	U
		mg/L												
TKN†	Plant-free	17.0	8.4	16.0	8.2	14.7	7.1	27.4	12.3	4.7	20.7	12.5	3.8	19.3
	Bamboo	17.0	8.4	15.9	6.7	12.1	5.9	22.6	8.9	2.6	13.5	9.3	4.6	17.5
	Rush	17.0	8.4	15.7	7.0	7.8	2.1	11.5	5.9	1.7	8.9	5.7	3.0	11.1
	Reed‡	16.1	5.3						2.9	1.8	6.2			
	Cattail	11.8	6.5	13.2	6.4				4.7	2.4	9.2	6.1	2.2	10.3
NH_3-N	Plant-free	9.2	5.8	10.9	5.5	9.8	2.7	14.6	8.5	3.2	14.2	8.8	2.5	13.3
	Bamboo	9.2	5.8	11.4	5.1	5.8	2.7	10.6	2.7	2.4	7.0	2.5	2.6	7.1
	Rush	9.2	5.8	11.1	6.5	1.2	0.9	2.8	0.8	1.0	2.6	0.1	0.1	0.3
	Reed‡	12.4	4.8						0.6	0.5	1.5			
	Cattail	10.9	5.6	11.6	6.2				0.6	0.5	1.2	0.4	0.4	1.2
TP§	Plant-free	6.2	1.5	5.7	1.5	5.9	1.4	8.3	5.5	1.3	7.8	7.5	3.0	12.9
	Bamboo	6.2	1.5	6.2	1.3	5.8	2.1	9.6	5.7	2.3	9.8	7.1	1.9	10.6
	Rush	6.2	1.5	6.0	1.5	4.9	1.9	8.3	4.2	2.2	8.1	6.0	1.8	9.1
	Reed‡	4.4	1.2						2.0	0.6	3.1			
	Cattail	5.3	3.4	5.9	3.3				3.0	1.9	6.6	3.4	1.8	6.8

† TKN = Total Kjeldahl N.
‡ Data published by Wolverton, 1982.
§ Total P.

vals. Atmospheric greenhouse temperatures were recorded daily. The 5-d biochemical O_2 demand (BOD_5), total Kjeldahl N (TKN), and ammonia-N (NH_3-N) were determined on each sample (APHA, 1976).

Nine procedures, outlined below, were conducted with a cattail and a plant-free system, which had been conditioned with sewage for > 2 months during March and April 1981. During this period, troughs with rush and bamboo were established and conditioned in the same manner. Starting in late May 1981, 13 of the same procedures were performed with the new systems and a plant-free system. The cattail experiments did not continue during the summer, because the greenhouse was too hot to sustain them in a healthy condition. The rush and bamboo did not seem to be affected by the heat during midday.

For each of these procedures, 72 L of raw sewage was pumped from the influent manhole at the National Space Technology Laboratories' Sewage Lagoon no. 1 directly into each settling tank, and transported back to the greenhouse. An initial sample was taken, plus another one after 6 h of settling from only one of the settling tanks. At the end of 24 h, aliquots were taken from each of the settling tanks prior to pumping the contents into each respective trough. Further samples were taken via valves at the bottom of the troughs at 6-, 24-, and 48-h intervals.

Each of the samples, except the 6-h settling samples, were analyzed for pH, BOD_5, total suspended solids (TSS), total dissolved solids (TDS), TKN, NH_3-N, and total P (TP) (APHA, 1976). The only analyses performed on the 6 h settling sample were BOD_5 and TSS. Atmospheric greenhouse temperatures were taken daily. The filter effluent temperatures were taken at the time of sample collection.

In December 1981, six procedures using tap water spiked with KNO_3 were performed in a manner similar to the previous experiments, except the solution was not held for 24 h prior to introducing it into the troughs. The plant-free, bamboo, and reed troughs were the only ones used. The cattail system was eliminated in the summer and not re-established. The rush trough was in the process of being repaired at this time, and NH_3-N, TKN, NO_3-N were performed on all

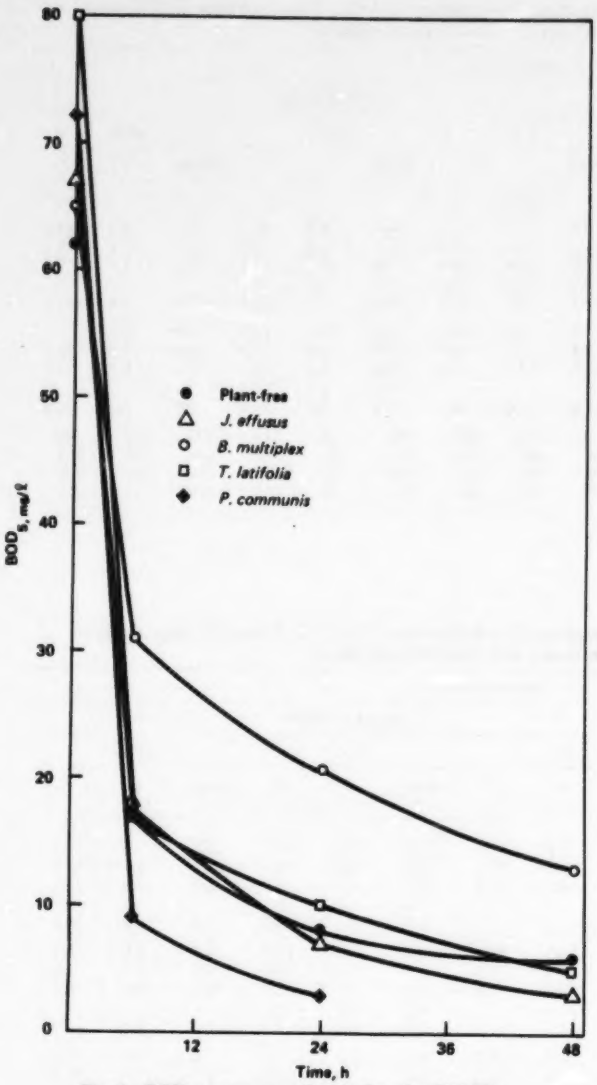


Fig. 2—BOD, vs. exposure time in the microbial filter.

samples; TP, pH, and temperature measurements were made on initial and final samples.

In March, six sewage experiments were performed again in a manner similar to the first experiments. The cattail system was added and the monitoring consisted of the analyses outlined for the tap water. The initial sample was removed after the waste water, which had been in the settling tank 24 h, was spiked with ammonium nitrate (NH_4NO_3). Once it was established that the NH_3-N was not converted to NO_3-N, 10 procedures using sewage, spiked with ammonium nitrate, were performed with the same monitoring schedule.

RESULTS AND DISCUSSION

Table 1 contains the mean, standard deviation (σ), and upper limit (U) concentrations of BOD_5, TSS, and TDS data obtained from the series of batch experiments conducted with each species. The upper limit concentrations are the maximum concentrations at the 95% confidence level ($P = 0.95$) computed by the equation:

$$U = \text{mean} + t_{0.95(n-1)}(\sigma)$$

Table 3—Mean atmospheric and filter effluent temperatures measured during each respective experimental period for which data appears in Table 1 and 2.

Experiment	Mean temperature		
	Atmospheric		
	Minimum	Maximum	Filter effluent
	°C		
Bamboo	23.0	37.5	26.1
Cattail	16.0	34.3	25.0
Reed	17.0	40.0	23.0

where σ is the standard deviation, and $t_{0.95(n-1)}$ is a numerical quantity for $n-1$ degrees of freedom (Ostle, 1972). Data by Wolverton (1982) on a reed-microbial filter evaluated under similar conditions is included for comparative purposes.

According to the data presented in Table 1 and Fig. 2, a plant-free microbial filter is as efficient in carbonaceous BOD_5 removal as one supporting the growth of rush or cattail. The terrestrial species, bamboo, performed the poorest in BOD_5 removal in comparison with the other systems. Although the mean BOD_5 values for all filters except the bamboo were under the 30 mg/L EPA requirement for secondary treatment after 6 h of treatment, only the reed system's performance was consistent enough to compute an upper limit value of 20.5 mg/L, well under 30 mg/L, at the 95% confidence level. However, after 24 h of exposure, the performances of all filters, except the bamboo, were efficient enough to bring the mean and the U value ($P = 0.95$) well below a 30 mg/L discharge requirement for BOD_5.

At this point, it must be pointed out that a significant portion of the BOD_5 reduction in the settling tank was a result of biodegradable solids settling out, and only the soluble BOD_5 substances passing into the filters. The settled solids also contain O_2-demanding substances, which require further detention in order for them to undergo complete anaerobic digestion and stabilization. If the liquid portion of the waste solution is left in contact with the settled solids, simpler, soluble substances can be released, which exert a BOD_5. The overall result is an initial drop in BOD_5, followed by a slight increase. This effect can be seen from the settling data in Table 1.

Unfortunately, the waste water collected at the National Space Technology Laboratories was low in TSS, as compared with municipal waste water. However, the settling tank was still incorporated into the experimental procedure, because it is definitely a necessary feature for large systems with high suspended solids in order to prevent filter clogging. Consequently, the TSS concentrations leaving the settling tanks after 24 h were under 30 mg/L (except for the previous reed study). After 24 h in the microbial filters, the statistical upper limits ($P = 0.95$) were all well under 30 mg/L, except for the cattail filter. The reed filter from a previous study was once again the superior system in TSS removal.

The dissolved solids tended to increase in all the systems over the 48-h exposure periods. The TDS increased by 12.2% in the plant-free system over the 48-h trough exposure period, 23.9% in the bamboo system, 36.4% in the rush system, and 24.3% in the cattail system. This was probably due to a concentration effect

Table 4—Mean reed system data for experiments conducted in January–February 1981, using waste water spiked with water hyacinth juice.

Parameter	Microbial filter	Concentration									
		Settling tank				Microbial filter					
		Initial		24 h		6 h		24 h		48 h	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
		mg/L									
BOD_5†	Plant-free	472	122	306	135	172	9	67	37	38	16
	Reed	461	134	318	130	97	52	36	21	21	17
TKN‡	Plant-free	27.9	1.3	23.8	2.5	16.3	2.0	13.3	1.6	12.0	1.6
	Reed	28.3	1.3	26.2	2.7	7.8	0.9	4.3	2.0	4.5	0.9
NH_3-N	Plant-free	13.0	3.9	11.1	3.5	9.7	1.7	7.7	1.4	7.3	0.5
	Reed	14.1	2.6	13.6	3.6	1.9	1.6	0.6	0.6	0.3	0.5

† BOD_5 = 5-d biochemical O_2 demand.
‡ TKN = Total Kjeldahl N.

Table 5—Mean N data for experimental systems treating tap water spiked with KNO_3.

Microbial filter	Parameter	Mean concentration							
		Initial		6 h		24 h		48 h	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ
		mg/L							
Plant-free	NO_3-N	12.3	1.2	5.3	2.0	1.6	1.2	0.25	0.25
Bamboo		11.8	1.2	2.6	1.0	0.05	0.02	0.05	0.02
Reed		12.3	0.9	3.3	0.64	0.39	0.39	0.05	0.05
Plant-free	NH_3-N	0.2	0.1	2.1	1.3	1.9	0.9	2.2	0.8
Bamboo		0.2	0.2	0.3	0.6	0.5	0.6	0.2	0.1
Reed		0.2	0.2	0.1	0.2	0.1	0.1	0.2	0.2
Plant-free	TKN†	2.6	0.7	4.3	0.6	4.3	0.6	5.0	1.1
Bamboo		2.5	0.6	4.0	1.3	3.3	1.0	3.6	0.9
Reed		2.5	0.7	2.8	0.8	3.5	2.0	3.1	1.0

† TKN = Total Kjeldahl N.

Table 6—Mean N data for the experimental systems treating plain waste water just prior to those studies with NH_4NO_3-spiked waste water.

Microbial filter	Parameter	Mean concentration							
		Initial†		6 h		24 h		48 h	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ
		mg/L							
Plant-free	NO_3-N	0.08	0.03	0.14	0.006	0.17	0.09	0.15	0.03
Cattail		0.11	0.03	0.19	0.09	0.19	0.09	0.22	0.12
Rush		0.09	0.04	0.15	0.10	0.13	0.08	0.10	0.03
Reed		0.13	0.10	0.22	0.10	0.49	0.25	0.42	0.03
Plant-free	NH_3-N	15.0	3.0	12.3	0.9	12.0	1.2	11.6	1.0
Cattail		15.7	4.2	6.5	1.3	4.6	1.3	3.0	1.0
Rush		16.7	4.1	5.7	1.0	3.4	1.2	2.4	1.1
Reed		15.1	3.1	1.9	0.4	0.6	0.4	0.7	0.6
Plant-free	TKN‡	20.0	3.6	16.3	2.0	15.1	1.9	15.4	1.0
Cattail		21.0	4.0	10.3	1.2	7.8	0.5	5.4	1.1
Rush		21.4	3.3	10.3	1.2	7.0	0.4	5.8	1.1
Reed		18.4	3.3	6.5	0.3	5.0	0.8	5.2	1.7

† Initial sample was taken from the settling tanks in which waste water was allowed to anaerobically settle and digest for 24 h, and then spiked with NH_4NO_3 just prior to introducing them into the filters.
‡ TKN = Total Kjeldahl N.

from the loss of liquid through evaporation or evapotranspiration. However, volume reductions in these experiments were not measured. The volume loss was monitored in the earlier reed experiments conducted by Wolverton (1982). In these experiments, the reed and plant-free systems lost an average of 21.8 and 12.3%, respectively, of their original volume over a 48-h period.

The total P data presented in Table 2 indicates little reduction ir this nutrient by any of the systems except the cattail. In fact, the total P concentration slightly increased over the experimental period for the plant-free and bamboo systems. A combination of evaporation and evapotranspiration, and lack of significant plant absorption created this effect.

The most striking difference in the plant-free system and those containing plants is in Kjeldahl and NH_3-N reduction rates after 24 h (Table 2). The rush and cattail filters reduced the NH_3-N by 93 and 95%, respectively, after 24 h. In fact, 89% of the NH_3-N in the rush filter was gone in just 6 h. The bamboo filter was more efficient than the plant-free system, but less so than the other two. It reduced the NH_3-N by 49 and 76% after 6 and 24 h, respectively. The Kjeldahl N, a measure of the total organic and NH_3-N concentration, was reduced by all systems in a pattern similar to that of NH_3-N. Statistically, the rush, reed, and cattail filters were superior in both TKN and NH_3-N removal to the plant-free filter.

The greenhouse and filter effluent temperatures for this series of experiments are presented in Table 3.

The initial mean waste water pH varied from 6.9 to 7.2. The mean, 48-h pH of the effluent from the plant-free filter was 7.3, the bamboo and rush filters were 7.0, and the cattail filter was 6.6.

Based on the superior results of the first reed study by Wolverton (1976), further experiments were conducted with reed to determine its response to waste solutions much higher in unstabilized contaminants. Therefore, raw sewage was mixed with water hyacinth juice to produce a solution significantly higher in BOD_5 than that used in the first experiments. The BOD_5 and N analyses of these experiments are presented in Table 4.

With the high BOD_5 waste solution, the BOD_5 of the waste water was reduced by 33% during the initial 24-h process in the settling tank. The average BOD_5 and TKN leaving the settling tanks were 312 and 24.0 mg/L, respectively. On a mass basis, the TKN requires 4.57 times its mass in O_2 for complete oxidation. Therefore, of the remaining BOD_5, approximately two-thirds is carbonaceous BOD_5 with the remaining nitrogenous. In the reed filter, the BOD_5 reduction of both forms is a single-step process as demonstrated by the rapid reduction in BOD_5, TKN, and NH_3-N in just 6 h. The plant-free system's BOD_5 remained approximately two times higher than the reed system over the same exposure time; the BOD_5 vs. exposure time is presented in Fig. 3.

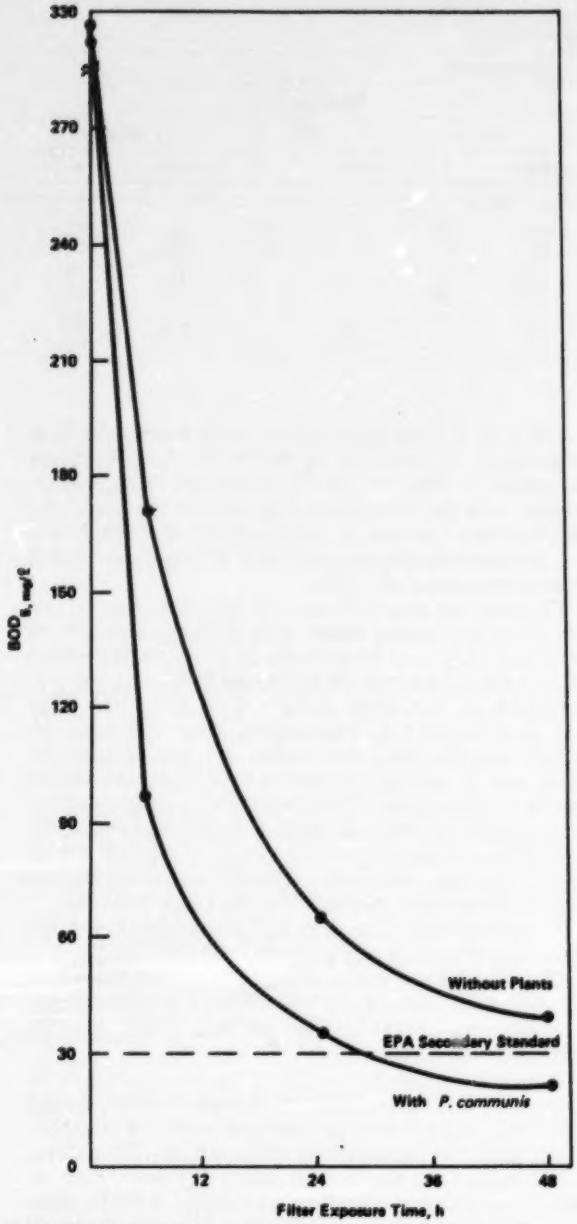


Fig. 3—BOD_5 vs. exposure time for the *P. communis* experiments with high BOD_5 waste.

In order to meet secondary BOD_5 standards of 30 mg/L, a minimum exposure time of 29 h in the combination filter would be needed if the BOD_5 entering the filter were approximately 300 mg/L.

The last three sets of data generated using tap water spiked with NH_4NO_3, plain waste water, and waste water spiked with NH_4NO_3, were performed in order to get a clearer picture of the N conversion processes in the filters. The data presented in Table 5 for those experiments conducted with NH_4NO_3-spiked tap water indicates that the plant-free filter used in these studies did effect denitrification as demonstrated by the NO_3-N loss, without significant corresponding increases in the

Table 7—Mean N data for experimental systems treating waste water spiked with NH_4NO_3.

Microbial filter	Parameter	Mean concentration: Initial† Mean	Initial† σ	6 h Mean	6 h σ	24 h Mean	24 h σ	48 h Mean	48 h σ
		mg/L							
Plant-free	NO_3-N	14.6	1.6	0.43	0.47	0.11	0.02	0.28	0.23
Bamboo		14.5	1.8	0.12	0.03	0.15	0.06	0.17	0.06
Rush		13.9	1.8	3.7	2.4	0.72	0.88	0.50	0.77
Reed		14.5	1.8	1.6	1.3	0.16	0.08	0.22	0.14
Plant-free	NH_3-N	33.3	6.4	22.7	3.9	20.8	0.8	19.8	3.0
Bamboo		33.0	5.6	16.5	3.5	14.5	3.0	12.2	2.6
Rush		33.6	7.4	16.7	3.0	14.6	2.3	14.2	3.3
Reed		32.6	6.7	5.9	2.2	0.5	0.7	0.2	0.1
Plant-free	TKN‡	51.1	3.5	25.6	0.7	23.8	2.1	23.7	2.4
Bamboo		50.3	9.8	21.2	3.2	16.8	3.6	15.0	3.7
Rush		52.4	5.7	20.7	2.8	16.9	2.2	17.2	3.2
Reed		42.3	8.7	11.6	5.8	4.4	1.1	4.0	1.0

† Initial sample was taken from the settling tanks in which waste water was allowed to anaerobically settle and digest for 24 h, and then spiked with NH_4NO_3 just prior to introducing them into the filters.
‡ TKN = Total Kjeldahl N.

NH_3-N or TKN. The addition of either bamboo or reed into the system increased the rate of denitrification over that in a plant-free filter.

The data presented in Table 6 for NH_3-N and TKN was very similar to that already presented in Table 2. One exception was that the data for the rush filter indicates that perhaps this filter's capacity for NH_3-N removal was exceeded. In Table 2, the rush filter was capable of reducing NH_3-N from 11.1 mg/L to 1.2 mg/L in 6 h; in Table 6, the rush filter reduced the NH_3-N from 16.7 mg/L to only 5.7 mg/L in 6 h. No significant increase in NO_3-N occurred as indicated by the data in Table 6. Therefore, the NH_3-N in the filters containing plants must have been absorbed by the plants or converted to a N form, which was then converted to N_2 and lost from solution to the atmosphere. Considering that the plants' coverage of the filters was at a maximum, and they were not cut back during this study period, plant absorption of the NH_3-N was probably insignificant compared with the latter explanation for the loss of NH_3-N without an increase in TKN or NO_3-N.

The data presented in Table 7 is especially interesting. The plant-free filter performed in a normal anaerobic mode, performing "anoxic" denitrification, a process by which NO_3-N is converted to N_2 without O_2, without efficiently converting NH_3-N or TKN to nonorganic forms. The bamboo and rush filters performed similar to the plant-free filter, with only a slight improvement in NH_3-N reduction. The NH_3-N removal capacities of these filters exposed to initial NH_3-N concentrations of approximately 33 mg/L had been exceeded. The bamboo and rush filters can handle NH_3-N levels of approximately 11 mg/L as demonstrated in Table 2.

However, the reed filter demonstrated efficiency in the removal of both oxidized and reduced N forms. From the data presented in Table 7, the TKN, a measure of the organic-N and NH_3-N (the reduced N form), in the reed filter was reduced by 90.5% from 42.3 to 4.0 mg/L in 48 h. The NO_3-N (the major oxidized N form present) was reduced at the same time by 98.5% from 14.5 to 0.22 mg/L in 48 h. Therefore, the overall TN (TKN + NO_3-N) was reduced by 92.6% from 56.8 to

Table 8—Mean, TP, pH, and effluent and atmospheric temperatures for the studies focusing on N removal in Table 5–7.

Microbial filter	System	TP†				pH				Effluent temp.				Atm. temp.			
		I‡		48 h		I		48 h		I		48 h		Min		Max	
		Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ	Mean	σ
		mg/L								°C							
Plant-free	Tap water with KNO_3	3.2	2.6	3.7	2.7	8.1	0.3	7.4	0.1	17.7	1.8	16.4	1.8	11.0	3.0	33.1	6.1
	Waste water	3.4	1.1	5.0	1.0	7.1	0.3	7.4	0.3	20.6	1.1	19.5	3.7	12.7	2.5	36.5	6.5
	Waste water with NH_4NO_3	4.5	2.4	2.4	1.2	7.1	0.1	7.7	0.2	22.6	1.1	21.6	2.7	17.1	4.2	36.9	4.3
Bamboo	Tap water with KNO_3	3.3	2.6	3.4	2.4	8.3	0.2	7.0	0.2	17.9	2.1	16.4	1.8	11.0	3.0	33.1	6.1
	Waste water	3.7	1.2	2.1	0.4	7.0	0.2	7.0	0.1	20.3	1.0	19.8	3.7	12.7	2.5	36.5	6.5
	Waste water with NH_4NO_3	5.7	1.6	1.6	1.2	7.2	0.2	7.1	0.1	22.5	1.1	21.6	2.6	17.1	4.2	36.9	4.3
Rush	Waste water	3.9	0.9	1.5	1.2	7.1	0.4	7.0	0.1	20.4	1.3	19.0	3.2	12.7	2.5	36.5	6.5
	Waste water with NH_4NO_3	4.4	2.6	1.7	2.2	7.1	0.1	7.3	0.1	22.7	0.9	21.6	2.7	17.1	4.2	36.9	4.3
Reed	Tap water with KNO_3	3.6	2.9	2.9	2.7	8.4	0.2	7.1	0.2	17.7	2.0	16.4	1.8	11.0	3.0	33.1	6.1
	Waste water	3.6	0.9	2.3	1.3	7.1	0.4	7.0	0.1	20.6	1.1	19.1	3.3	12.7	2.5	36.5	6.5
	Waste water with NH_4NO_3	5.0	2.0	1.5	2.1	7.1	0.1	6.9	0.1	22.1	0.9	21.6	2.6	17.1	4.2	36.9	4.3

† TP = Total P.
‡ I = Initial reading.

4.22 mg/L. Since both NH_3-N and NO_3-N are rapidly lost in the reed filter, it suggests that the plant roots are contributing sufficient O_2 to the liquid to enhance nitrification, but not enough to sustain this zone in a complete aerobic state. Therefore, anoxic conditions conducive to denitrification prevail. Since nitrite is an intermediate in both the nitrification and denitrification processes, the most probable N pathway is:

$$\text{organic N} \xrightarrow{\text{ammonification}} NH_4^+ \xrightarrow{\text{partial nitrification}} NO_2^- \xrightarrow{\text{denitrification}} N_2$$

The mean TP, pH, and effluent temperatures for these last three sets of data are compiled in Table 8 for background information.

CONCLUSIONS

In conclusion, a plant-free microbial filter is more effective in carbonaceous BOD_5 removal than in nitrogenous BOD_5 removal. When vascular aquatic plants are added to the filter, NH_3-N removal is enhanced, and nitrogenous BOD_5 removal is improved.

A reed-microbial filter system is not only efficient in NH_3-N removal, but also in NO_3-N removal. The data suggests that both forms are being converted to the common, intermediary NO_2-N, and then to gaseous N_2 evolved from the system. Consequently, the reed-microbial filter is the superior system studied to date.

The data suggests that raw sewage with initial BOD_5's of approximately 100 mg/L can be treated to meet secondary standards following 6 h in an anaerobic settling tank and 6 h in plant-free, reed, rush, or cattail filters under the conditions of these experiments. The reed filter is statistically more reliable at the 6 h detention time.

When reed-microbial filters are used to treat waste water with initial BOD_5's of approximately 450 mg/L, 24 h in the settling tank, and 29 h in the filter are required to meet the 30 mg/L standard for secondary treatment.

LITERATURE CITED

1. American Public Health Association. 1976. Standard methods for the examination of water and wastewater. 14th ed. Am. Public Health Assoc., Washington, D.C.
2. Dinges, R. 1978. Upgrading stabilization pond effluent by water hyacinth culture. J. Water Pollut. Control Fed. 50:833–845.
3. Duffer, W. R., and J. E. Moyer. 1978. Municipal wastewater aquaculture. USEPA 600/2-78-110. National Technical Information Service, Springfield, Va.
4. Jewell, W. J., M. S. Switzenbaum, and J. W. Morris. 1981. Municipal wastewater treatment with anaerobic attached microbial film expanded bed process. J. Water Pollut. Control Fed. 53:482–490.
5. Koon, J. H., G. M. Davis, R. K. Genung, and W. W. Pitt, Jr. 1979. The feasibility of an anaerobic upflow fixed-film process for treating small sewage flows. Conference on Energy Optimization of Water and Wastewater Management for Municipal and Industrial Applications, New Orleans, La. December 1979.
6. Metcalf & Eddy, Inc. 1979. Wastewater engineering: treatment/disposal/reuse. 2nd ed. p. 455–460. McGraw-Hill Book Co., New York.
7. O'Brien, W. J. 1981. Use of aquatic macrophytes for wastewater treatment. J. Environ. Eng. Div., Am. Soc. Civ. Eng. 107(EE4): 681–698.
8. Ostle, B. 1972. Statistics in research. p. 89–92. The Iowa State University Press. Ames, Iowa.
9. Stephenson, M., G. Turner, P. Pope, J. Colt, A. Knight, and G. Tchobanoglous. 1980. The use and potential of aquatic species for wastewater treatment. Publ. no. 65. California State Water Resources Control Board. Sacramento, Calif.
10. Switzenbaum, M. S., and W. J. Jewell. 1978. Anaerobic attached film expanded bed reactor treatment of dilute organics. U.S. Dep. of Energy Rep. TID-29398. National Technical Information Service, Springfield, Va.
11. Tourbier, J., and R. W. Pierson, Jr. (ed.). 1976. Biological control of pollution. University of Penn. Press. Philadelphia.
12. Wolverton, B. C. 1979. Engineering design data for small vascular aquatic plant wastewater treatment systems. p. 179–192. Proc. Aquaculture Systems for Wastewater Treatment Seminar. Univ. of Calif., Davis.
13. Wolverton, B. C. 1982. Hybrid wastewater treatment system using anaerobic microorganisms and reed (*Phragmites communis*). Econ. Bot. 36:373–380.
14. Wolverton, B. C., and R. C. McDonald. 1979. Upgrading facultative wastewater lagoons with vascular aquatic plants. J. Water Pollut. Control Fed. 51:305–313.
15. Young, J. C., and P. L. McCarty. 1969. The anaerobic filter for waste treatment. J. Water Pollut. Control Fed. 41:160–173.